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TECHNOLOGY UTILIZATION REPORT

Technology Utilization Division

THE ELECTROMAGNETIC HAMMER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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THE ELECTROMAGNETIC HAMMER

From

GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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NOTICE

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FOREWORD

The Administrator of the National Aeronautics and Space Administration has established a technology-utilization program for "rapid dissemination of information . . . on technological developments . . . which appear to be useful for general industrial application." From a variety of sources, including NASA Research Centers and NASA contractors, space-related technology is collected and screened, and that which has potential industrial use is made generally available to American industry. Information developed in the Nation's space program includes the latest developments in materials, processes, products, techniques, management systems, and analytical and design procedures. This publication is part of a series intended to provide such technical information.

This report covers the results of experimental work conducted by Republic Aviation, Incorporated, and Advanced Kinetics, Incorporated, on magnetic coil design and development for NASA. It was prepared by Daniel E. Strohecker, Alfred F. Leatherman, and George T. Ruck of Battelle Memorial Institute, from material supplied by Marshall Space Flight Center. A method of using electromagnetic forces for removing the distortion from welded components has been under investigation at George C. Marshall Space Flight Center and by NASA contractors. The method consists of using a pancake electromagnetic coil driven by electric-discharge equipment to correct distortion in metal components such as welded rocket fuel tanks, gore segments, and bulkheads. The process is unusual in that no tooling other than the magnetic coil is required. In a typical application the magnetic hammer has been used to smooth out distortions in fuel tank domes for the giant Saturn V launch vehicle.

The Director, Technology Utilization Division
National Aeronautics and Space Administration

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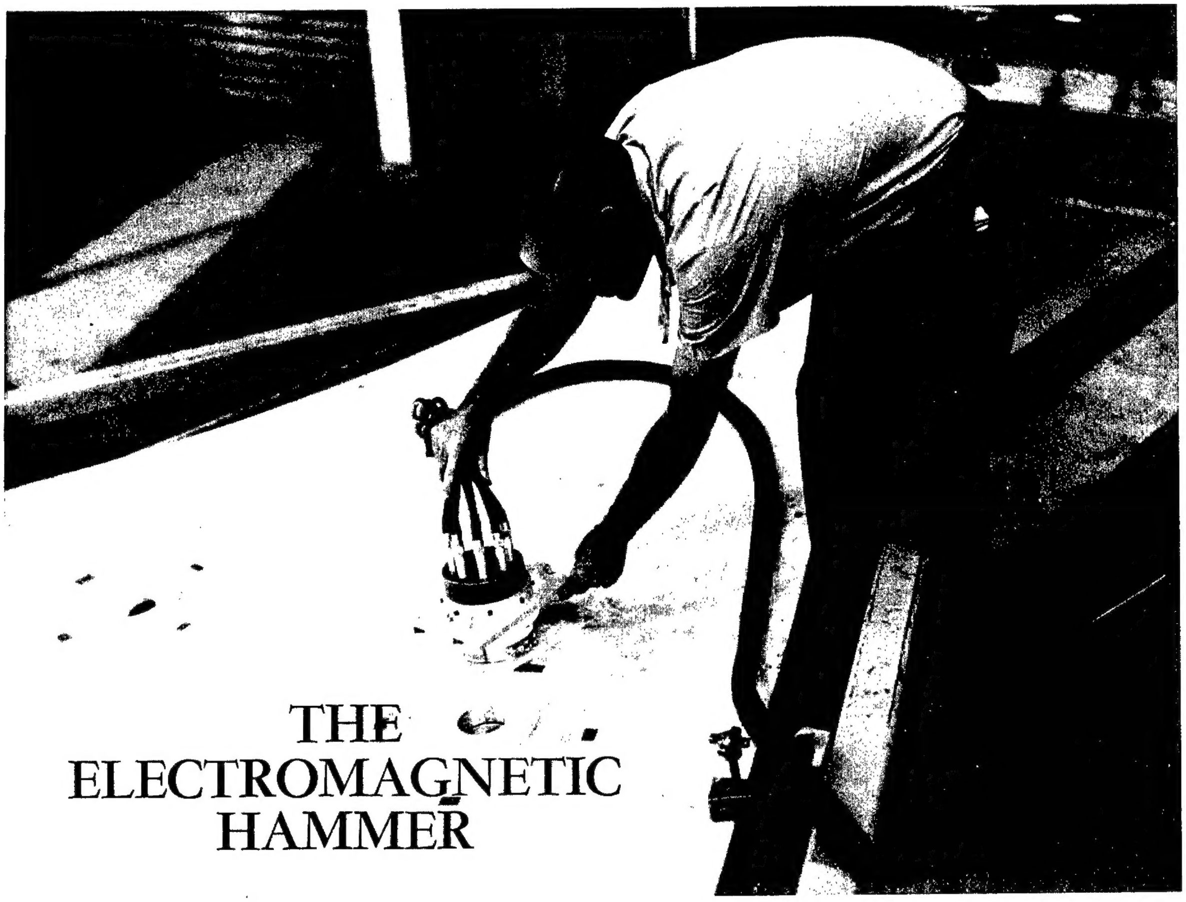


THE ELECTROMAGNETIC HAMMER

INTRODUCTION

Distortion of fabricated components, resulting either from processing or handling, has been a problem for manufacturers of both military hardware and commercial products. Attempting to remove distortion caused by welding is usually a time-consuming hand-labor operation. The experimental electromagnetic hammers described in this report are useful tools for the removal of distortion by bending or stretching the part to the desired contour. The electromagnetic hammer can apply a fairly uniform, controlled pressure over an area corresponding to the size of the coil and can thereby correct shapes without a die.

The electromagnetic hammer, so called because it can be used in place of a hammer, consists of five essential parts: a power source, capacitors for storing energy, switches, transmission lines, and a magnetic coil. Since sufficient information on the first four items is available in trade literature, the primary emphasis of this report is on the magnetic coil. A brief description of energy storage and transmission technology is included in the Appendix to give some background.

A typical coil consists of a spirally wound and insulated heavy conductor. The coil shown in figure 1 (ref. 1) was wound with glass fabric insulation and encapsulated in epoxy resin. It was then mounted in a holder which is used to position the coil with respect to the work surface. The holder may also be used to absorb the recoil from the hammering operation.

The purpose of this report is to provide a definitive description of experimental electromagnetic hammers, set forth preliminary operational characteristics found by NASA contractors, and present in sufficient detail the constructional lines followed so that others may experiment with the electromagnetic hammer for further development and new applications. Another objective of this summary is to stimulate further investigation and development of magnetic hammers through the dissemination of preliminary experimental information.

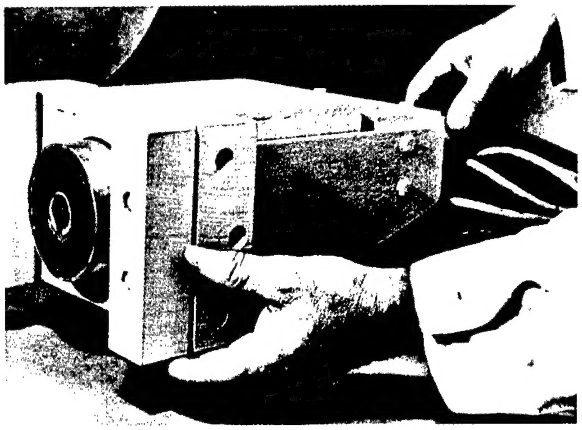


Figure 1.—Four-inch, 10-turn aluminum-encased coil assembled with pneumatic damping cylinder (ref. 1).

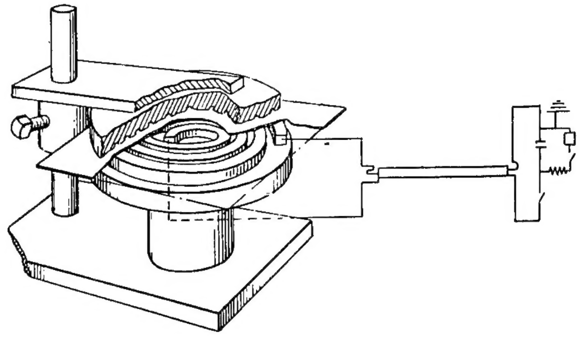


Figure 2.—Pancake coil for electromagnetic forming of sheet described in a U.S. patent (ref. 1).

PRIOR STATE OF THE ART

The use of electromagnetic forces to drive machinery is quite old. The direct application of electromagnetic forces for metalworking is, however, a recent innovation of old principles. The development of this field has been pronounced over the last 10 years because of new capabilities in storage and rapid release of electrical energy. A patent on a "Metal Forming Device and Method" was issued to G. W. Harvey in the United States in March of 1961 (ref. 2). Figure 2 shows a magnetic coil and application which was disclosed for magnetic forming in this patent. The patent rights were assigned to General Dynamics Corporation, New York, N.Y. (GD).

Electromagnetic forces have been a useful tool of man since their inception and are now commonplace in our homes and factories in motors, generators, and selenoids. New uses for electromagnetics have been dependent on the development of stronger magnetic fields. As an outgrowth of controlled fusion experiments under the Atomic Energy Commission's Project Sherwood (ref. 3) and independently by Furth and Waniek (ref. 4) at Harvard Cyclotron Laboratory in about 1954, high-intensity magnetic fields became a reality. About the same time, considerable interest in high-velocity forming of metals was aroused in the aerospace industry. The need for better methods for fabricating new high-strength materials was the main driving force behind this development.

It was natural, therefore, that electromagnetic forces should become one of the prime energy sources of interest for high-velocity metal-forming operations. In 1958 GD manufactured and marketed the first commercial electromagnetic metalworking equipment which could be used for swaging tubing and making mechanical connections on coaxial electrical cable. Certain features of magnetic forming such as the absence of contact with the workpiece, friction, fluids, valves, and moving parts made the process very attractive for space applications. Robert Schwinghamer visualized the potentials of the process and undertook additional research on new applications both at NASA Marshall Space Flight Center and at laboratories of NASA contractors. The development of the electromagnetic hammer is one of the results of this research effort. Models of electromagnetic hammers have been investigated under NASA programs by both Republic Aviation Corporation (RAC), under the leadership of G. Pfanner (ref. 1), and by Advanced Kinetics, Incorporated (AK), under the direction of Dr. R. W. Waniek (ref. 5). The investigations conducted in the latter two programs were limited to the development of electromagnetic coils for removing distortion from welded rocket fuel tanks. The method has also been applied to removing distortion from gore segments and bulkheads in work conducted at MSFC. The potential scope of application is believed to be much larger.

METAL DEFORMATION BY ELECTROMAGNETIC-HAMMER TECHNIQUES

The material to be deformed must be considered as part of the total system in magnetic

forming since its characteristics can materially change the amount of deformation for a given amount of stored energy. The conductivity of the material will determine the effectiveness of energy conversion to magnetic forces. As the conductivity of the material is decreased, energy losses take place due to heating of the workpiece. Consequently, a more conductive material such as copper or aluminum will be deformed more at the same energy level than will a low-conductivity metal like stainless steel. The magnetic hammer cannot be used directly on nonconductive workpieces.

Factors important in using the electromagnetic hammer have been investigated by AK, by work with 3.9-, 7.9-, and 11.8-inch-diameter coils (ref. 5). In addition, three coils with inductances of 0.37, 3.4, and 2.3 μh and a diameter of 3.9 inches were used. The coils were connected to a 150-μf capacitor bank with an internal 0.15-μh inductance for all test results presented here. The plastic-deflection data from magnetic forming were obtained using a free-forming tool where the diameter of the tool was larger than the diameter of the magnetic coil. The results of these studies at AK, are presented in the following paragraphs.

The initial amount of energy stored in the capacitor bank was determined from the equation

$$W=\frac{CV^2}{2},$$

where

W=energy, joules
C=capacitance, f
V bank voltage, v

When all other factors are equal, the strength of the material determines how much deformation results from a given amount of energy. As the strength of the material increases, the amount of deformation decreases. Based on data from AK (ref. 5), figure 3 shows the difference in deformation produced by supplying equal amounts of energy to 4052–H32 and 6061–T6 aluminum alloys. The former has a yield strength of 23 000 psi minimum, while the latter has a yield strength of 35 000 psi minimum. The increase in yield strength of 12 000 psi reduced the plastic deflection by approximately 0.035-inch for the various energy levels investigated.

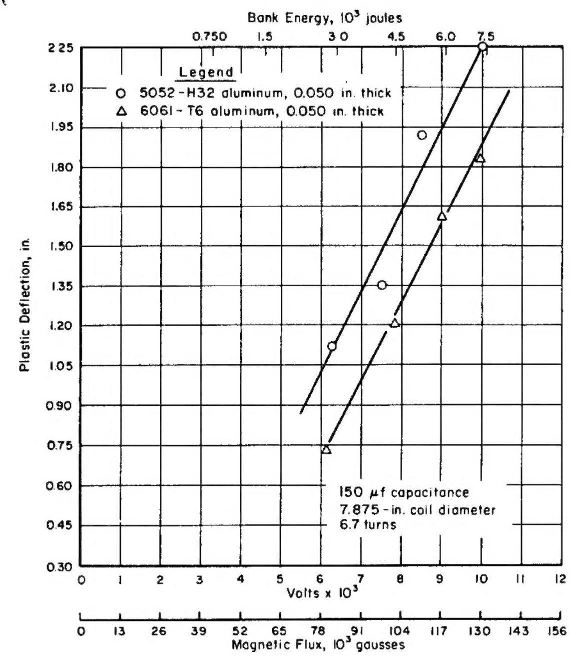


Figure 3.—Plastic deflection at the center of free-formed aluminum sheets produced by electromagnetic hammers operated at various energy levels (ref. 5).

A change in thickness of the sheet material being deformed will have a similar effect on the amount of deformation obtained. Figure 4 shows that the amount of deflection decreases with increasing material thickness for the same energy level and coil design (ref. 5). Since the plots appear to be linear with respect to energy for both material strength and thickness, it would be expected that the deformation should be predictable by the standard engineering deflection formulas. The change of slope of the plot in the case of changing material thickness lends credence to this opinion.

If the deforming section is considered as a diaphragm with simply supported edges and a uniform load, the maximum deflection in the elastic range would be

$$D=\frac{2wr^4}{3Et^3}$$

where

D=deflection, inches
w=distributed load, psi
r=radius, inches
E=modulus of elasticity, psi
t=material thickness, inches

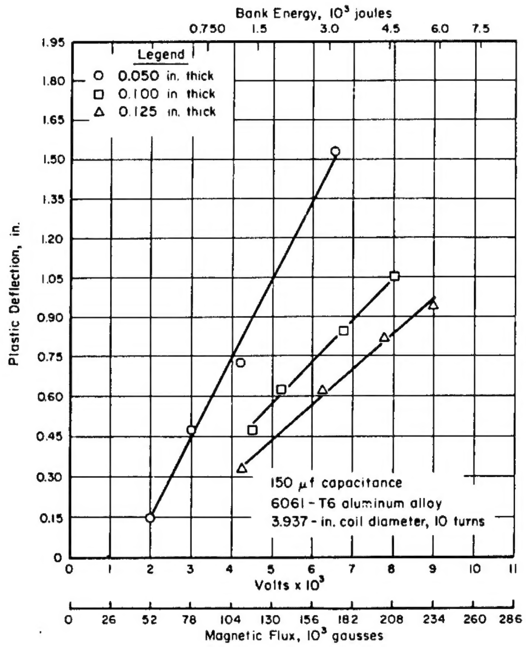


Figure 4.—Effect of discharge energy on the plastic deformation produced by electromagnetic hammers on free-formed aluminum sheets of three different thicknesses (ref. 5).

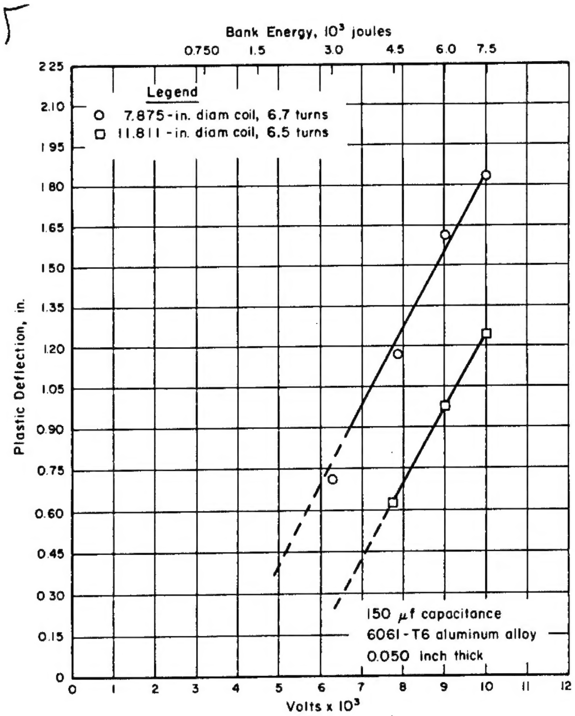


Figure 5.—Plastic deflection at the center of free-formed aluminum sheets for various energy levels discharged through coils of different diameters (ref. 5).

If $d\sigma/d\epsilon$, the slope of the stress-strain diagram in the plastic region, is substituted for E, the formula should hold reasonably well for the case of plastic deformation. Therefore, the change in yield strength as reflected in E is inversely proportional to the deflection, so that deflection-energy plots for materials with the same modulus but different strengths would be expected to be parallel as shown in figure 3. Since the deflection is inversely proportional to the cube root of the thickness, data plotted as in figure 4 should not fit parallel trend lines.

The effect of coil diameter on the amount of deformation obtained in the AK studies is given in figure 5 (ref. 5). It appears that an increase in coil diameter will result in a decrease in deformation for a given number of coil turns and energy level for thin-sheet materials. This is probably due to spreading the same amount of energy over a larger area so that more energy is used in simply overcoming the elastic limits of the material before plastic deformation can be initiated.

An apparent effect of changing coil inductance is seen in figure 6 for the amount of deformation produced by coils with the same diameter and energy level but with a different number of turns (ref. 5). The coil with the larger number of turns gave the greatest amount of plastic deflection for a given energy level. The load applied in electromagnetic forming is not uniform over the entire surface of the workpiece under the coil (ref. 1). The effects of coil size and energy level on the deflection of free-formed sheet aluminum are shown in figure 7. The radius of the deformed material decreases with increasing energy for both the 4- and 12-inch-diameter coils used by RA in their study. However, the decrease in dome radius with increasing energy appears to be less severe with the larger coil than with the smaller as might be expected from figure 7. A 240-µf capacitor bank was connected to the magnetic coils through a vacuum switch and coaxial leads in this test series. The material was free-formed without the use of any backing tooling.

Exact solutions for the design of an electromagnetic hammer are not available, so that only general trends obtained from experimental coils have been presented. Exact solutions may be possible, but would probably require a highly sophisticated computer program for each coil application. At least two problems must be

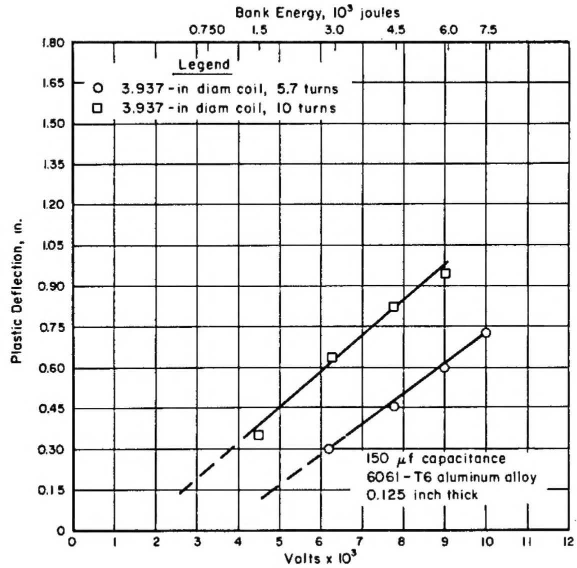


Figure 6.—Plastic deflection and energy for two coils of the same diameter but different number of turns (ref. 5).

solved to obtain the exact solutions: (1) magnetic field distribution of the coil including effects of the workpiece and (2) mechanical behavior of the workpiece under various field distributions. With solutions of those two problems, it might be possible to optimize the coil designs for various workpiece materials, thicknesses, initial contours, desired final contours, etc. For practical applications, however, it will be necessary to have a limited number of coils which will work with the desired workpieces and produce a range of contours by changing the energy input to the system.

A summary of the apparent effects of various parameter changes on the deflection of material opposite the coil, with all other parameters being held constant, is given in table I. This summary may be used for general guidance in the construction of experimental coils. However, the characteristics of the electric-discharge equipment must be considered in any evaluation

P6

Table I.—Summary of electrogmagnetic-parameter effects on deflection of free-formed sheet aluminum, based on figures 3 through 6

Increasing parameter	Causes deflection to
Coil diameter	Increase
Number of wire turns in coil	Increase
Energy stored in discharge unit	Increase
Distance between coil and workpiece	Decrease
Material strength	Decrease
Material thickness	Decrease
Material resistance	Decrease

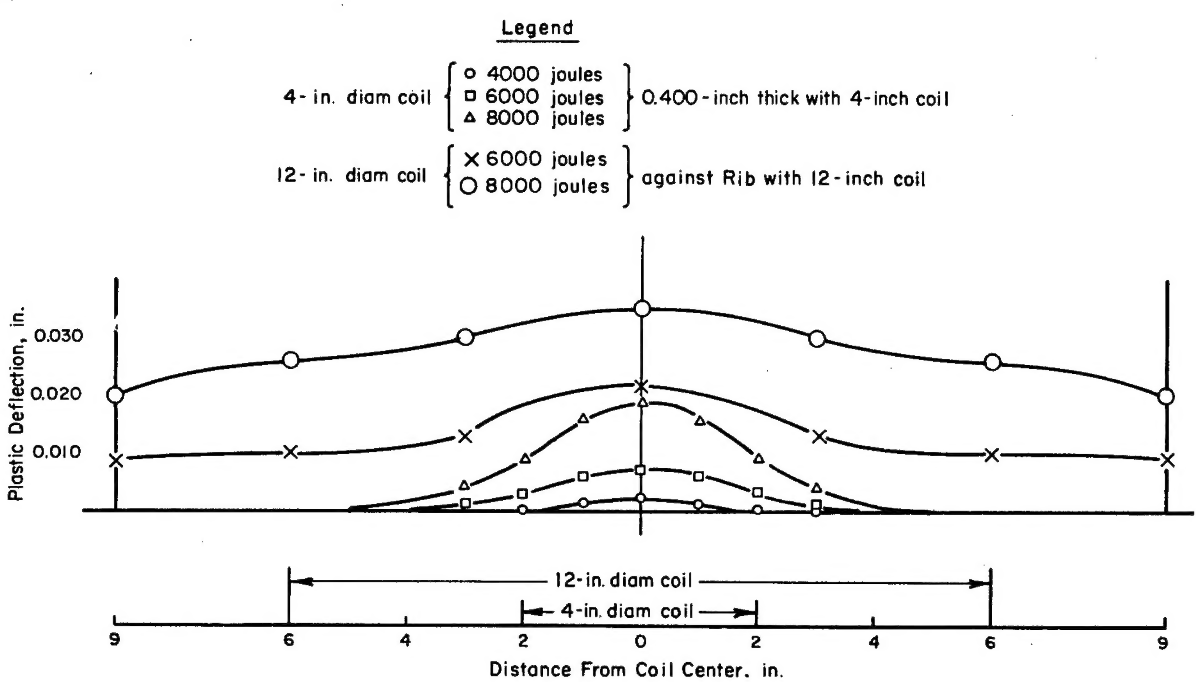


Figure 7.—Effect of discharge energy on plastic deflection measured from the coil center of free-formed 5456–H323 aluminum alloy sheets (ref. 1).

of a total electromagnetic forming system. A more detailed treatment of the electrical aspects of coil design is given in the Appendix.

MANUFACTURE OF EXPERIMENTAL ELECTROMAGNETIC COILS (ref. 1)

During the development of the electromagnetic hammer at RAC, two sizes of coils were made and tested. The first coil, shown in figure 8, was 4.12 inches in diameter and contained 10 turns. The second coil, shown in figure 9, was 11.94 inches in diameter and contained 40 turns. The coils were encapsulated in epoxy plastic which was molded into a piston-like shape. These coil designs were used for the experimental forming of aluminum sheet up to 0.500-inch gage. Other coil designs might be preferable for other forming operations or materials.

During the program a number of epoxy-resin compositions were explored to determine which would give the best results in service under various loading conditions and temperatures of operation. The epoxy plastic which could be cured at room temperature (C–100) was relatively soft and did not crack under the impact loads developed in the experimental testing at RAC. However, the heating resulting from repeated discharges caused softening and distortion. The coil could not be operated above 150° F. A thermal-setting epoxy resin was found to be satisfactory in the experimental program for encapsulating coils which could operate continuously at temperatures up to 350° F. It had the following composition:

Wt %	
55.5	Epirez 5091 (Jones-Dabney Company)
33.3	LP3 (Thiokol Chemical)
11.2	Curing Agent "Z" (Shell Chemical)

Coils 4 inches in diameter encapsulated with this plastic withstood discharge energies of 7500 to 9500 joules at a rate of five discharges per minute for a total of 75 discharges without distortion or softening of the plastic. A coil temperature of 150° F was measured at the completion of the test.

The room-temperature-cured plastic should be satisfactory for low-energy slow-discharge electromagnetic-coil applications. The high-temperature-cured plastic must be used, however, where the coils are to be cycled at a high rate.

Procedure Used for the Manufacture of Experimental 4-Inch-Diameter 10-Turn Coil (ref. 1)

(1) Wrap wire and BP908–181 epoxy-impregnated glass-cloth strip, or equivalent, for 10 turns. Coil laminated as follows: first 3 turns with 3 laminates, next 4 turns with 1 laminate, and last 3 turns with 3 laminates.

(2) Apply Scotchweld EC1386 adhesive (Minnesota Mining & Mfg. Co.) to both coil faces, filling voids.

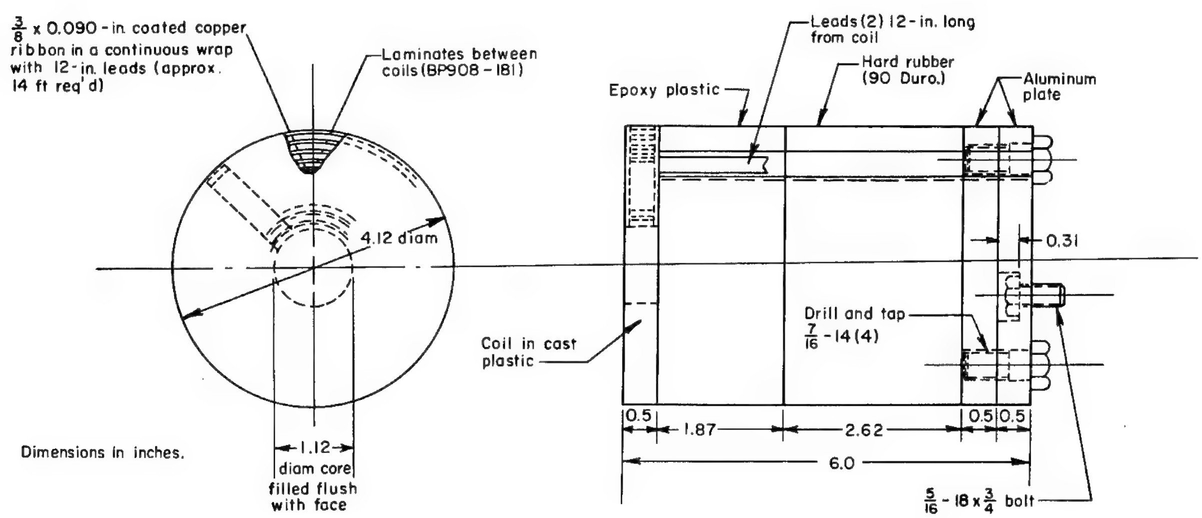


Figure 8.—Four-inch-diameter 10-turn electromagnetic coil (ref. 1).

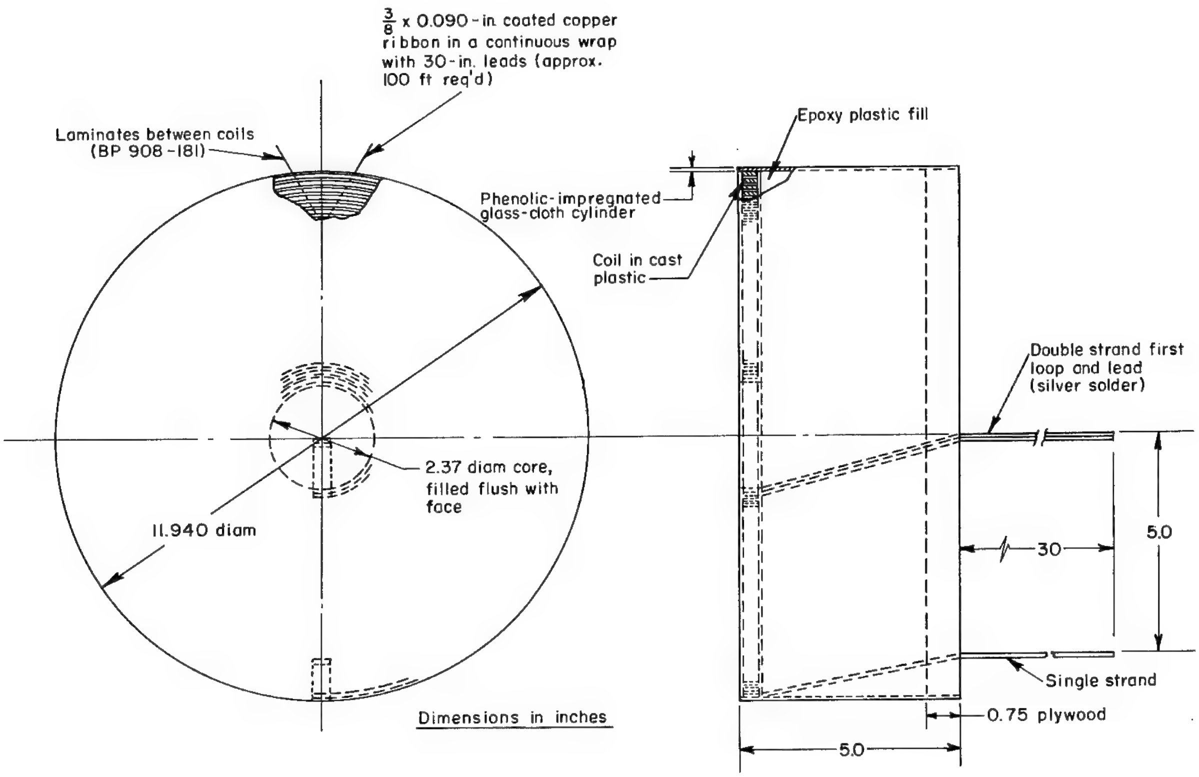


Figure 9.—Twelve-inch-diameter 40-turn electromagnetic coil (ref. 1).

(3) Oven cure for 1 hour at 350° F using pressure plates against each coil surface.
(4) Wrap coil completely using BP908–181 (or equivalent) epoxy-impregnated glass cloth.
(5) Oven cure for 90 minutes at 325° F.
(6) Encapsulate coil using −100 epoxy resin,[1] and cure at room temperature.
(7) Cement rubber block of 90 Durometer hardness to cured epoxy face, using epoxy-resin adhesive (as in item 6 above) and cure at room temperature.
(8) Cement aluminum plate to rubber block, using epoxy-resin adhesive (as in item 6 above) and cure at room temperature.

Procedure Used for the Manufacture of Experimental 12-Inch-Diameter 40-Turn Coil (ref. 1)

(1) Wrap wire and BP908–181 epoxy-impregnated glass-cloth strip, or equivalent, for 40 turns with the coil laminated as follows: first 3 turns with 3 laminates, second 3 turns with 2 laminates, next 28 turns with 1 laminate, next 3 turns with 2 laminates, and last 3 turns with 3 laminates.
(2) Oven cure for 90 minutes at 325° F, using pressure plates against each coil surface.
(3) Apply Scotchweld EC1386 adhesive (Minnesota Mining & Mfg. Co.) to both coil faces, filling the voids.
(4) Oven cure for 1 hour at 350° F, using pressure plates against each coil surface.
(5) Wrap coil completely using BP908–181 (or equivalent) epoxy-impregnated glass cloth, applying 3 laminates on each coil face and 10 laminates (strips) around outer periphery, and enclosing the entire coil with 1 covering layer.
(6) Oven cure for 90 minutes at 325° F, using pressure plates against each coil surface.
(7) Locate coil in phenolic-impregnated glass-cloth cylinder (item 10 for manufacturing instructions) and encapsulate coil using epoxy resin [1] and room-temperature cure.

[1] Composition:

Wt %	
51	Epirex 5091 (Jones-Dabney Company)
43.8	LP3 (Thiokol Chemical)
5.2	Diethylenetriamine

(8) Cement plywood backing to epoxy face, using epoxy-resin adhesive (as per item 7) and cure at room-temperature.

(9) Pot plywood backing to phenolic-impregnated glass-cloth cylinder using epoxy-resin adhesive and cure at room-temperature.

(10) Manufacture phenolic-impregnated glass-cloth cylinder as follows:

   (a) Wrap tightly 6 turns of phenolic-impregnated glass cloth 6 inches wide around 11.70-inch-diameter mandrel.

   (b) Cover wrap glass cloth with adhesive tape.

   (c) Oven cure for 3 hours at 350° F.

   (d) Remove from mandrel and peel outer wrap, including adhesive tape covering.

ENERGY-CARRYING CAPACITIES OF EXPERIMENTAL ELECTROMAGNETIC COILS (ref. 1)

Destruction tests were run by RAC on both the 4- and 12-inch-diameter coils. The 4-inch coil was tested with a 240-μf capacitor bank, coaxial leads, and a vacuum-discharge switch. The total system had a ring frequency of 4600 cps. It was found that 14 000 joules could be withstood by the 4-inch-diameter coils on this system without any visible sign of failure. An energy level of 17 300 joules resulted in spalling of the coil plastic face, while 20 000 joules separated the coil from the plastic body. As the energy level was increased to 25 000 joules, the glass-cloth insulation separated from the coil face, and finally at 27 500 joules, the leads broke away from the coil. All of the coil destruction tests were run with the coil rigidly attached to a ⅛-inch-thick aluminum sheet.

The 12-inch-diameter coil was connected through coaxial lines and a vacuum switch to a 960-μf capacitor bank. The coil was attached to a ½-inch-thick aluminum plate during the test and the energy level was increased to 48 000 joules with no visible sign of damage when tested on the Republic Aviation electric-discharge system.

The 4-inch-diameter coil operated at an energy level of 12 000 joules plastically deflected a 0.400-inch-thick aluminum sheet 0.070 inches at the center of the coil. The 12-inch-diameter coil operated at an energy level of 8500 joules provided a deformation of 0.050 inch in a 0.200-inch-thick aluminum sheet with heavy stiffeners.

APPLICATIONS FOR THE ELECTROMAGNETIC HAMMER

There should be many applications for the electromagnetic hammer in metalworking operations where relatively uniform pressure is to be applied over a localized area. Most other metalworking processes involve the use of tools which contact the material over the area to be formed and cause nonuniform deformation. The greater uniformity of deformation obtainable by this process has been demonstrated in work on removing the distortion from large welded rocket fuel tanks. Any other type of distortion which can be corrected by slight bending or stretching of the metal might also be considered an application, such as removal of heat-treating distortion.

The coils can be made small and light for portable tooling and connected to a remote power supply by cables. A portable tool with the unusual capabilities of the magnetic hammer would seem to have a potential for use along assembly lines for the removal of distortion from sheet-metal-formed components. The automobile or appliance industry might find such equipment a useful addition to their assembly lines.

The best application for the tool appears to be in operations which require small deflections of an area of sheet- or plate-formed parts to bring them to the desired contour. Such operations do not generally require additional tooling and can be conducted by a semiskilled craftsman.

One limitation of the process is that it can be used only when no change in surface area or when only a slight amount of stretching is desired. Compression or shrinking of the metal to the desired contour is not possible without additional tooling. end

Coils which could be cycled rapidly to produce repeated impacts might be used for such operations as metal spinning. The lack of contact between the tool and workpiece would be especially desirable when a high-quality surface finish is desired. The electromatic hammer might prove useful for other metalworking op-

erations requiring the application of a load on a small area of the workpiece at any one time. The possibilities are limited only by the imagination of future engineers who have specialized requirements for new methods of metalworking.

The research which has been carried out by NASA has shown the capabilities of the process, and it is now the commercial applications which will reap the harvest from this unique innovation for metalworking.

Appendix: BACKGROUND CONSIDERATIONS IN MAGNETIC HAMMER DESIGN AND OPERATION

ENERGY SYSTEM

One of the most important advantages of the capacitor discharge technique is the ability to deliver extremely large amounts of power into a relatively small space. Even a fairly modest discharge supply can deliver electrical impulses in the millions of kilovolt-amperes. The method can be used where power is required over only a short time interval, or a succession of intervals. The basic ingredients of a capacitor discharge system include a power supply to charge the capacitors, the capacitors themselves, a heavy-duty switching device to close the circuit between the capacitors and energy transducer, and the transducer.

The basic arrangement of the component units of the energy system are illustrated schematically in figure 10.

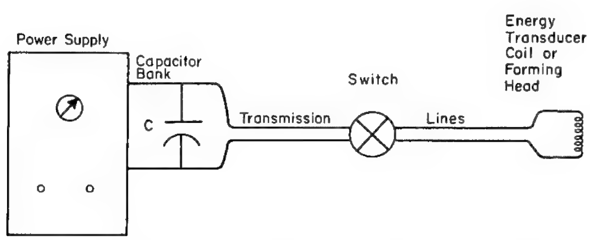


Figure 10.—Schematic arrangement of energy system.

Power Supply (ref. 6)

The power supply performs the function of converting the available commercial alternating current (ac) into direct current (dc) for charging the capacitor bank, C. Various simple means for controlling the circuit used are considered below. The capacitor charge voltage levels commonly used are 3 to 20 kv or 30 kv.

A conventional oil-filled transformer with tube rectifiers is generally used in the power supply because of the high voltage requirement.

The "charging time" desired generally determines the power-supply size and cost, since faster charge cycles require higher continuous current outputs.

Several charging methods are used, such as the monocyclic network, the Marx surge charge circuit, constant-current charging, and the simple resistance-limited charging scheme. The last two types may be the most common and simplest, except where very fast charges are required.

A variable autotransformer in the primary of the power-supply transformer can be used to adjust the transformer output voltage so as to provide fairly good, constant-current charging. On the other hand, the high-voltage and power-dissipation problems associated with resistance-limited charging can be alleviated somewhat by immersing the limiting resistors in transformer oil.

Capacitor Bank (ref. 6)

Generally, capacitors specifically intended for rapid discharge service are preferable, especially when various new experimental arrangements are being evaluated. Energy storage capacitors can be roughly categorized as slow, medium, or fast, according to the internal inductance which controls the maximum possible speed of discharge, or, to put it another way, according to the capacitor ring frequency. The capacitor ring frequency sets the upper current and frequency limit in an electric discharge system. Generally, the "medium" capacitors with ring frequencies of 100 to 200 kc are the types most suitable in magnetic forming.

A typical cost figure for capacitors of this type is 10 to 15 cents per joule, while the cost per joule based on a completely packaged system (charger, capacitors, and switching) can run as high as 50 cents or more per joule. These capacitors have a finite life span, however, and typical guarantees range all the way from

1000 to a few million or so maximum level discharges, depending on the percentage of voltage reversal. Although individual energy storage capacitors are available in ratings of a few tenths to several hundred microfarads at voltages from 3 kv to over 100 kv, most systems currently in use are rated 20 kv or less, to minimize dielectric breakdown problems.

Capacitor life expectancy depends very much on the following parameters:

(1) *Voltage Stress.* Operation at 75 per cent or less of the rated voltage usually can be expected to increase life expectancy by a factor of 7 to 9.

(2) *Ringing Frequency.* Operation at about 30 per cent of the capacitor ring frequency will increase the life expectancy by approximately half, and the relation is almost linear.

(3) *Voltage Reversal.* Controlling voltage reversal to achieve 50 per cent of the rated value can be expected to provide a life increase of perhaps 300 per cent.

(4) *Time on Charge.* It is difficult to assess derating due to this factor, but it is certainly true that long times at full charge decrease life expectancy. Ambient-temperature considerations generally are not much of a problem in typical forming apparatus.

During operation in a fast discharge circuit, the capacitor terminals may be subjected to very high electromechanical forces. Rigid construction techniques should be used in connecting the capacitors. The capacitor supplier probably can supply helpful information on connection details for the particular capacitors used.

Switching Devices (ref. 6)

The heavy-duty switch that connects the circuit from the capacitors to the coil can be selected from one of at least three types.

(1) *Air Ionization Gap Switch.* This type is comparatively simple and reliable and can handle up to ¼ megajoule or more, but it is limited in operating-voltage range for a particular gap setting and is definitely noisy. Also, tests at MSFC in the 20-kv range show jitter characteristics of up to 50 μsec in some versions. This is really not a problem when only one discharge at a time is required, but when synchronization is a requisite, it is definitely undesirable.

(2) *Partially Evacuated Gap Switch.* This type has the advantage of operation over a somewhat wider voltage and energy range. However, the vacuum equipment associated with operation of the switchgear adds considerably to system bulk, complexity, and cost. This switch is considerably less noisy than the air ionization switch, however.

(3) *Ignitron Switch.* After some rather exhaustive and time-consuming switch testing at MSFC, ignitrons were finally adopted for most of the forming circuits. Ignitrons require an ignitor, or trigger supply, but jitter characteristics are very good; they carry high currents, are compact, and are virtually noiseless in operation. The "A type 7703" seems to be a good choice for electrohydraulic and magnetic forming systems.

When it is desirable to "modulate" the capacitor bank output by means of programed discharge of several discrete bank elements, ignitrons are probably the best choice to satisfy all of the switching requirements. They are far more expensive than simple air ionization switches, however.

Transmission Lines (ref. 6)

The speed of discharge is limited by the capacitors and coil only when the inductance of the connecting circuit is negligible. Coil inductances commonly are on the order of a few microhenries or less. A separation of only an inch or two between the going and coming conductors that carry the energy from the capacitors to the coil will introduce several microhenries of inductance. If a very fast discharge is desired, very close spacings between wide parallel bus plates must be used, or a coaxial cable arrangement, so as to reduce the transmission-line inductance to negligible levels. The parallel, or flat-plate, line and coaxial cable are the two basic types of transmission line used in well-engineered electric discharge systems for forming purposes.

Flat-Plate Line

In designing a parallel plate line, the inductance and magnetic pressure generated between the closely spaced conductors are the primary items of interest. The inductance for a parallel plate transmission line is

$$L=\frac{\mu_0 d}{W} \text{ henries/m}$$

where

μ_0=MKS vacuum permeability ($4\pi\times10^{-7}$)
d=spacing between plates, m
W=width of plates, m.

The magnetic pressure generated between the plates is

$$P=2\pi\times10^{-12}\left(\frac{I}{W}\right)^2 \text{ atm}$$

where

I=current, amp
W=plate width, m.

Parallel plate construction frequently offers the very lowest inductance, but has the great disadvantage of inflexibility, so it is usually best suited for current-collector duty, such as paralleling capacitors, or for those cases where flexibility is not required. In addition, extreme care must be exercised in laying up parallel lines, as there is frequently as much as 10 000 to 20 000 volts across the two plates, which are separated by only 10 mils of dielectric material in a typical installation.

Coaxial Cable

A coaxial cable, on the other hand, is easier to install and has much greater flexibility. Then, too, the cable inherently has excellent force distribution characteristics because of the circular cross section. Also, voltage-breakdown problems frequently are less prevalent than with the parallel plate line, and the cable voltage ratings actually can be considerably exceeded in pulse applications such as magnetic forming.

A special low-inductance cable is now becoming popular, and this inductance can be a full order of magnitude lower than that of the RG 8/U-type coaxial cable, for example. Multiple paralleling of cables reduces inductance even further.

ELECTRIC DISCHARGE MODES (ref. 6) AND MATHEMATICAL RELATIONSHIPS FOR CAPACITOR DISCHARGES

Although the initial energy stored in the capacitor bank is direct current in character, the current flow that occurs during discharge is a continually changing transient that is rich in alternating current components. The changing discharge current causes a changing magnetic field in the coil which induces currents in the work upon which the metal-forming forces depend. The actual character of the current that flows upon closing the coil-capacitor circuit of figure 10 depends upon the values of inductance (L), capacitance (C), and an effective resistance (R) attributable to resistance coupled from the work into the coil plus circuit resistance. The current flow can assume one of three modes: oscillatory, critically damped, or overdamped. Although fairly common in electrical engineering, no discussion of an electric discharge forming system can be considered complete without giving due mathematical consideration to these transients. Accordingly, a mathematical treatment of the three transient conditions is included in the following paragraphs.

More frequently than not, the discharges are oscillatory. The overdamped mode is characterized by lower peak currents and relatively poor power transfer, so this mode usually is not desired. Perfect critical damping is almost impossible to maintain during a discharge because of the dynamic nature of some of the circuit parameters.

In magnetic-forming electric circuitry, the discharge current can follow one of the three basic modes of operation mentioned: oscillatory, critically damped, or overdamped.

These cases are discussed individually, and mathematical relations useful in designing circuits for electric discharge systems are provided. The following symbols are used in the discussions:

$$a=\frac{R}{2L}$$

$$B=\left(\frac{1}{LC}-\frac{R^2}{4L^2}\right)^{1/2}$$

C=capacitance, farads
e=2.718
f_r=resonant frequency, cps
E=voltage, v
$i_{(t)}$=current at any instant, amp
I_{max}=peak current at "first maximum", amp
$K=\left(\frac{R^2}{4L^2}-\frac{1}{LC}\right)^{1/2}$
L=inductance, henries
R=resistance, ohms
t=time, sec
t_{max}=time to current "first maximum", sec

Oscillatory Case

For an RLC circuit to be oscillatory, the following applies:

$$R^2<\frac{4L}{C}$$

The current at any instant is

$$i_{(t)}=\frac{E}{BL}\,\mathrm{e}^{-at}\sin Bt$$

The time to current "first maximum" is

$$t_{max}=\frac{1}{B}\tan^{-1}\frac{B}{a}$$

The peak current at "first maximum" is

$$I_{max}=E\left(\frac{C}{L}\right)^{1/2}\mathrm{e}^{-at_{max}}$$

The resonant frequency can then be found by

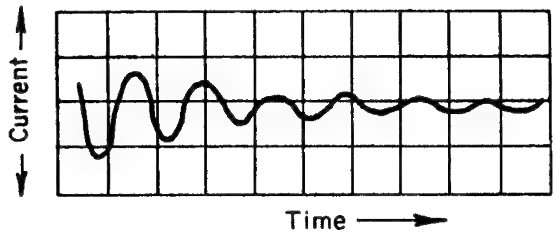
$$f_r=\frac{B}{2\pi}$$

If $R^2<<4L/C$, then the peak current equation can be reduced to:

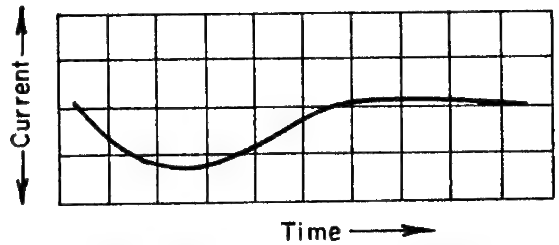
$$I_{max}=E\left(\frac{C}{L}\right)^{1/2}$$

Under these conditions, the resonant frequency is then

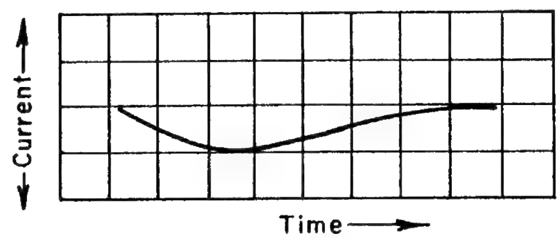
$$f_r=\frac{1}{2\pi(LC)^{1/2}}$$



a. Oscillatory Current



b. Approximately Critically Damped Current



c. Overdamped Current

Figure 11.—Modes of electric discharge (ref. 6).

Figure 11(a) shows a typical oscillatory discharge. Data are: energy, 500 joules; sweep rate, 100 μsec/cm (for scale-expansion purposes); current, 40,000 amp/cm; load, 3-in coil.

Critically Damped Case

For an RLC circuit to be critically damped, the following applies

$$R^2=\frac{4L}{C}$$

The current at any instant then is

$$i_{(t)}=\frac{Et}{L}\,\mathrm{e}^{-at}$$

The time to current maximum, or peak, is

$$t_{max}=\frac{2L}{R}$$

The peak current is

$$I_{max}=\frac{2E}{R\mathrm{e}}$$

Figure 11(b) shows a discharge that is approximately critically damped. Data are: energy, 5000 joules; sweep rate, 10 μsec/cm; current, 40,000 amp/cm; load, bridge wire in water.

Overdamped Case

For an *RLC* circuit to be overdamped, the following applies

$$R^2>\frac{4L}{C}$$

The current at any instant is

$$i_{(t)}=\frac{E}{KL}\,\mathrm{e}^{-at}\sinh Kt$$

The time to current maximum, or peak, is

$$t_{max}=\frac{1}{K}\tanh^{-1}\frac{K}{a}$$

The peak current is

$$I_{max}=E\left(\frac{C}{L}\right)^{1/2}\mathrm{e}^{-at_{max}}$$

Figure 11(c) shows an overdamped discharge. Data are: energy, 5000 joules; sweep rate, 10 μsec/cm; current, 40,000 amp/cm; load, bridge wire in water.

General Case

This peak current of the discharge in an energy-storage application in general is given by

$$I_{max}=\frac{E}{\left(R^2+\frac{L}{C}\right)^{1/2}}$$

This equation is a good approximation for most purposes.

INSTRUMENTATION AND ANALYSIS

The voltage applied initially to the coil upon closure of the discharge switch can be assumed, to a first approximation, to equal the direct-current charge level of the capacitors. If a continuous, reliable voltage measurement during the discharge is desired, considerable care should be exercised in arranging the measuring system. Because of the rapidly changing voltage, the use of a properly compensated attenuator is probably mandatory. Also, considerable care in design and means of connection is called for in any high-voltage circuit. A third complication involves possible spurious voltages in the attenuator or lead-wire circuits as a result of capacitive effects and electromagnetic coupling with the very large currents circulating in the discharge system.

Two methods of discharge-current measurement used most frequently are the conventional current-shunt approach similar to the technique used at lower powers and frequencies, and the use of a pickup coil similar in construction to a current transformer. In using a current shunt directly in series with the main current, the shunt should be located in the ground-return circuit to avoid high voltages in the instrument circuits. Since it is possible for such a shunt to become open circuited by overheating, resulting in hazardous and dangerous voltages in the instrument circuits, shunts are not preferred for high-current work. For lower current work and for calibration of other current-measuring devices, any shunt that is used must be designed to provide low inductance. Two versions of low-inductance shunts are the folded ribbon, or "Martin' type (ref. 7), and the coaxial type (ref. 6). Electrical compensation generally is not required with the current shunt and its resistance can be selected to permit direct display of the output by means of an oscilloscope. The measuring leads should be shielded to decrease pickup voltages from the discharge circuit.

The pickup-coil method for current measurement usually employs a toroidal coil that is constructed with sufficient insulation to permit its use directly on a high-voltage conductor. The coil design is sometimes referred to as a "Rogowski Coil" (refs. 7 and 8). An air-core design generally is used to extend the frequency response, with the current to be measured passing through the central opening of the toroid. Inasmuch as the pickup voltage is a differential function of the discharge current, an integrating circuit is used to compensate the pickup voltage depending on the characteristics of the pickup coil. Simple *R–C* circuits have been found to permit good calibration in terms of

the signal provided by shunt-type measurements.

Considerable information has been obtained at MSFC through the use of microflash photography for detecting forming sequences and rates (ref. 6). A microflash unit available from Edgerton, Gerneshausen, and Grier provided known flash repetition rates which could then be used to determine average deformation rates in a multiple exposure by noting the succesive positions of an index line on the specimen. Forming rates of up to 9000 cps were measured in swaging of aluminum tubing. Optical arrangements with photodetectors also are frequently used to measure rates and amounts of deformation.

SAFETY

Because of the high voltage and large amounts of stored energy present in charged capacitors, experimentation with capacitor-discharge systems requires extra attention to safety precautions. Work crews should consist of at least two men familiar with artificial resuscitation. All discharge equipment of experimental and final types should be fitted with thorough interlock and shorting-bar systems. On the other hand, upon the conclusion of experiment, and the assembly of working equipment with adequate insulation in closed cubicles, the capacitor discharge unit is probably no more dangerous than many home appliances.

ELECTRICAL ASPECTS OF COIL DESIGN

The electrical design of the coil for a magnetic hammer is concerned with defining the coil parameters which influence the electrical characteristics of the coil. Such parameters are the physical size, wire size, wire conductivity, number of turns, and the coil configuration.

The physical size of the coil is determined primarily by the area of metal to be formed, with the coil area to be approximately equal to the forming area. Experiments at RAC on forming 0.125-inch, 7075-O aluminum demonstrate that the area formed is essentially equal to the area of the forming coil and independent of the discharge energy (ref. 1).

The size and type of wire to be used in the coil is influenced by a number of factors. It is apparent that a minimum amount of energy should be dissipated as heat in the coil; this would require minimizing the resistance of the coil windings. Since the discharge current is usually oscillatory for magnetic hammer applications, the skin depth can be small and the current confined near the surface of the wire. Therefore the surface area of the wire used should be large in order to minimize the resistance; flat conductors are generally used for electromagnetic forming coils. Also, of course, the wire should have good conductivity. The wire size is also influenced by the total number of turns desired, since the coil diameter is fixed. An additional very important factor influencing the wire size is the mechanical strength required of the coil, and this factor will probably dominate the choice of wire size.

The number of turns desired on the coil depends in a complex fashion on a variety of factors. In order to accomplish any forming it is necessary that the magnetic field exert sufficient pressure to exceed the yield strength of the material. Since the field is proportional to the number of ampere turns in the coil, it might appear desirable to maximize the number of turns. However, the maximum current flowing in the coil is inversely proportional to the coil inductance, and thus decreases as the number of turns increases. Examining these relationships in more detail, the maximum magnetic pressure is proportional to $(NI_{max})^2$, while for an underdamped discharge where $L>>CR^2$, $I_{max}=V\sqrt{C/L}$, where V is the voltage applied to the capacitor bank. Now for a spiral pancake-type coil, the inductance can be expressed in the form $L=aN+bN^2$, where a and b are constants depending on the coil shape and dimensions. With this expression for the inductance, the maximum magnetic pressure becomes proportional to

$$N^2/(aN+bN^2) \text{ or } 1/[(a/N)+b].$$

Thus, it appears that increasing the number of turns will have no effect beyond a value which makes a/N small compared with b. For the normal spiral, a is usually small compared with b; thus the maximum magnetic pressure would appear to be essentially independent of the number of turns on the coil.

The minimum number of turns the coil must have will be determined primarily by the inherent inductance of the capacitor bank and the transmission lines connecting the bank to the

coil. In order to insure that the electrical energy stored in the capacitor bank is converted predominantly into magnetic energy which can be utilized in forming process, the ratio of the coil inductance to the inductance of the capacitor bank and transmission lines should be as large as practicable. The desired system inductance ratio will determine the minimum number of turns, while the maximum number of turns will be limited by the physical size of the coil and the requirement for maintaining a small coil resistance.

Magnetic Design

The magnetic design of a forming or magnetic hammer coil appears to be largely empirical in nature. This analytical determination of an optimum design would be a very difficult task and would require a better understanding of the physical mechanisms involved in the forming process than is currently available. It is known that the total magnetic force on a given volume of material can be obtained by integrating the Maxwell stress tensor over the surface area of the volume. However, determining the magnetic field values to use in evaluating the stress tensor requires the solution of a second-order partial-differential-boundary-value problem, which is very difficult for most geometries. In the case of a flat spiral coil being used for hammering essentially flat metal sheets, the magnetic pressure at a point is given by $B^2/8\pi$ in gaussian units, where B is the radical field of the coil in the presence of the workpiece.

The magnetic-field distribution of a given coil in the absence of the workpiece can be measured easily or can be computed, although not so easily if the coil is not wound uniformly. In general, for a uniformly wound spiral coil, the radial-field component has approximately a sinusoidal distribution across the coil, while the axial-field component can be described approximately by a displaced cosine distribution. These are shown for a particular coil in figures 12 and 13 (ref. 5). Also on these figures are shown the field distributions at the coil surface, when in the presence of a ½-inch aluminum sheet placed ⅜-inch away from the coil. It is apparent that the maximum radial field strength increases, while the axial-field components decrease. To relate the free-space field strengths with the field strengths in the presence of the workpiece is very difficult, since the presence of the workpiece changes the apparent inductance and ac resistance of the coil, thus modifying the discharge characteristics as well as the field distributions.

Some general comments regarding the magnetic effects of the coil can be made, even if quantitative results are not available. It is desirable that the discharge rates and the conductivity of the workpiece be high enough so that essentially no magnetic field penetrates the workpiece. In other words, the skin depth in the workpiece given by $\delta=(1/\sigma)/\sqrt{\pi f \mu \sigma}$ where f is frequency, μ is the magnetic permeability, and σ is the conductivity of the workpiece, should be less than the thickness of the workpiece. This is necessary for optimizing the net force on the workpiece available for forming. In addition, the workpiece must have good electrical conductivity to prevent dissipation of the magnetic field energy in heating the workpiece. This is what happens in general when magnetic forming of stainless is attempted, where the energy goes into heating the material and little deformation results.

RECOIL OF ELECTROMAGNETIC HAMMERS

For the 4-inch-diameter coil previously described, a 1-inch-diameter air cylinder operating at 90 psi provided the necessary damping action and returned the coil to the working position after each discharge (ref. 1). The coil and air cylinder were mounted in a Micarta cylinder which in turn could be attached to the part to be deformed. The 12-inch-diameter coil covered sufficient area that no air cylinder was required to overcome recoil. Instead, the coil was loosely mounted in a closed-end cylinder so that captive air during discharge was sufficient to return the coil to the workpiece.

An analysis of the recoil velocity for three different coil sizes was made by Advanced Kinetics (ref. 5). The characteristics of the coils used in their study are given in table II. Measurements were made of the coil recoil speed as influenced by the input energy to the coil. These data are plotted for the 3.937-, 7.875-, and 11.811-inch coils in figures 14, 15, and 16. It

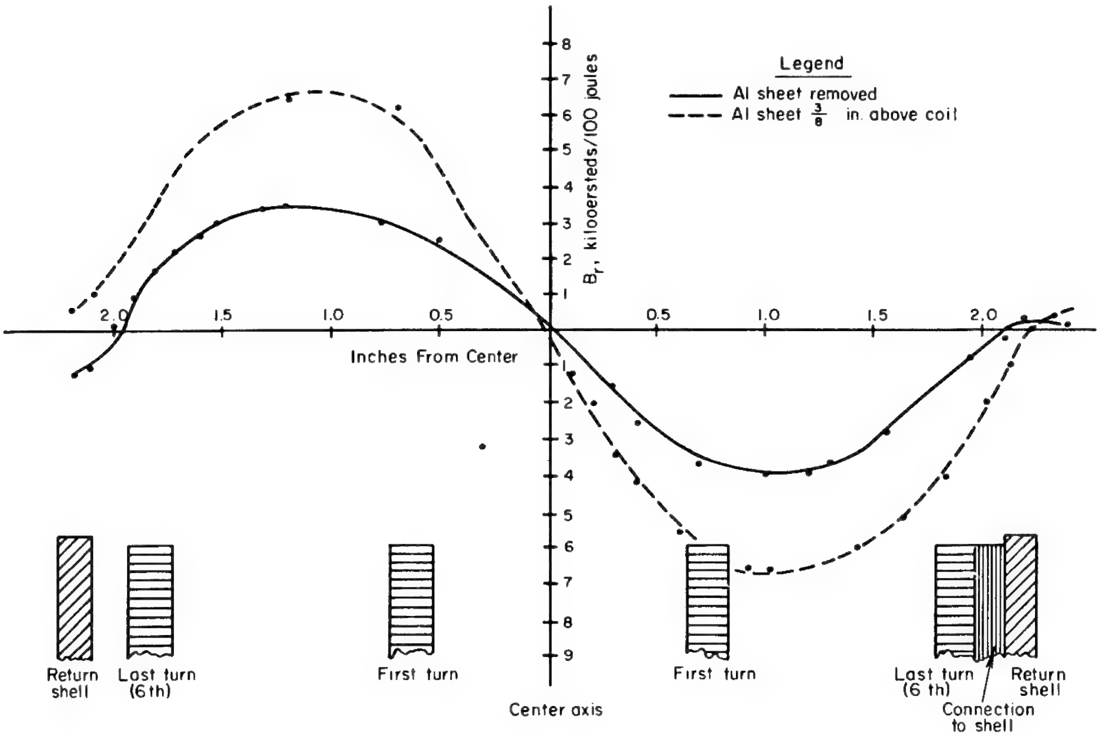


Figure 12.—Radial magnetic flux distribution for a 4-inch coil with and without the workpiece (ref. 5).

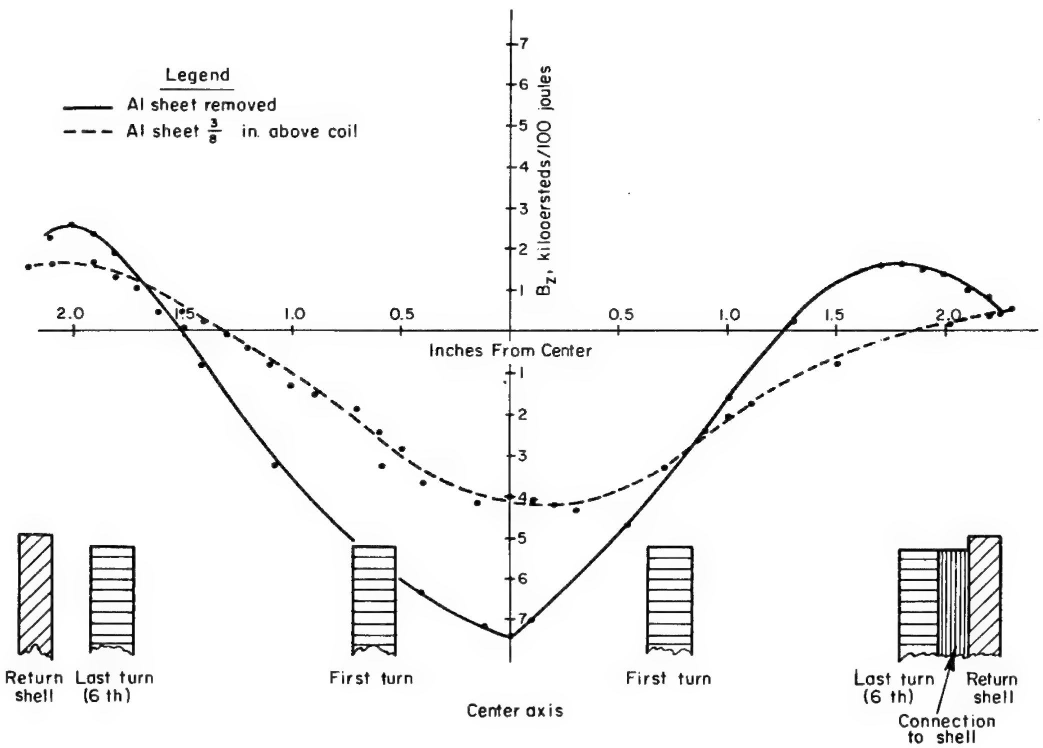


Figure 13.—Axial magnetic flux distribution for a 4-inch-diameter coil with and without the workpiece (ref. 5).

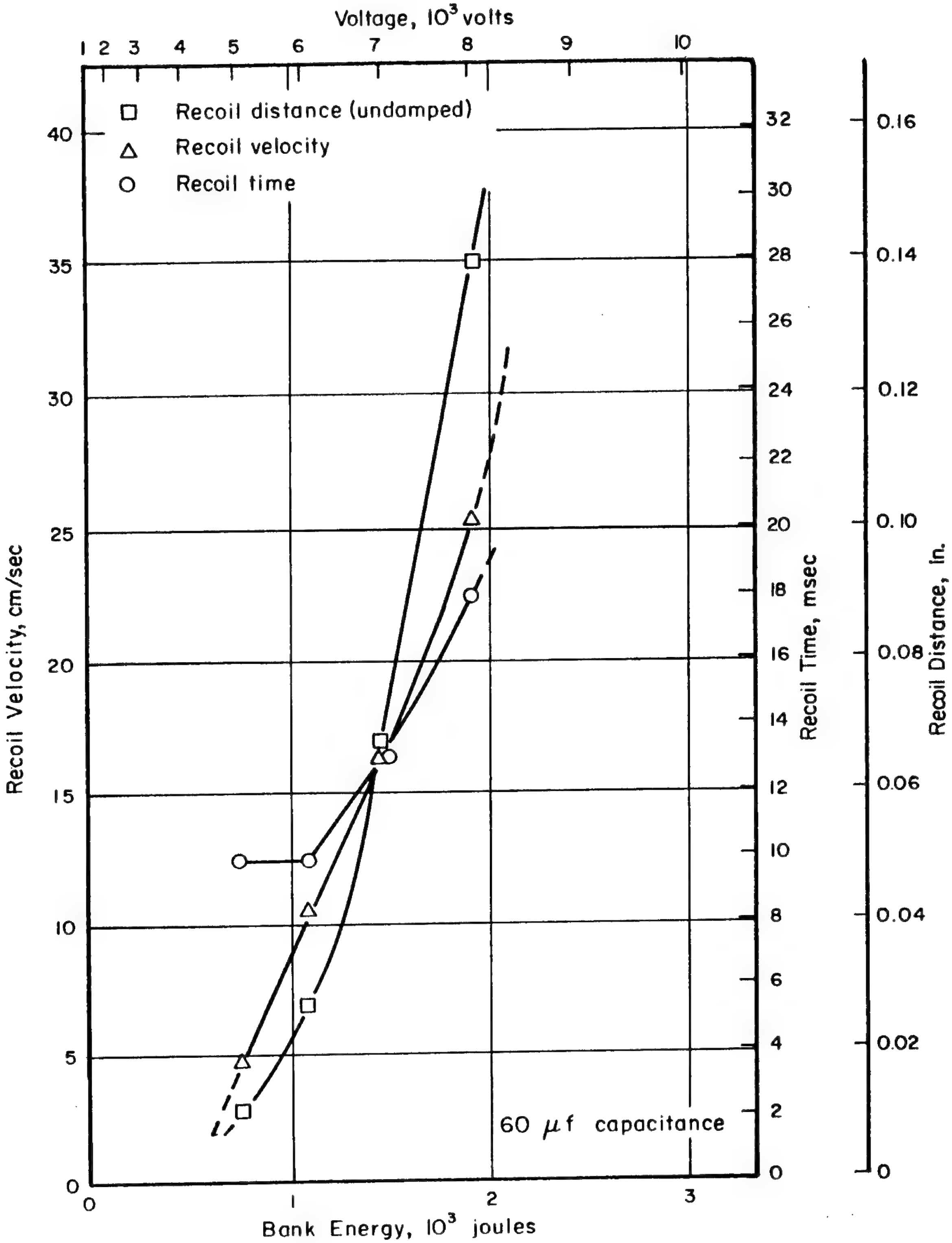


Figure 14.—Recoil data for hammer 1A described in table II (ref. 5).

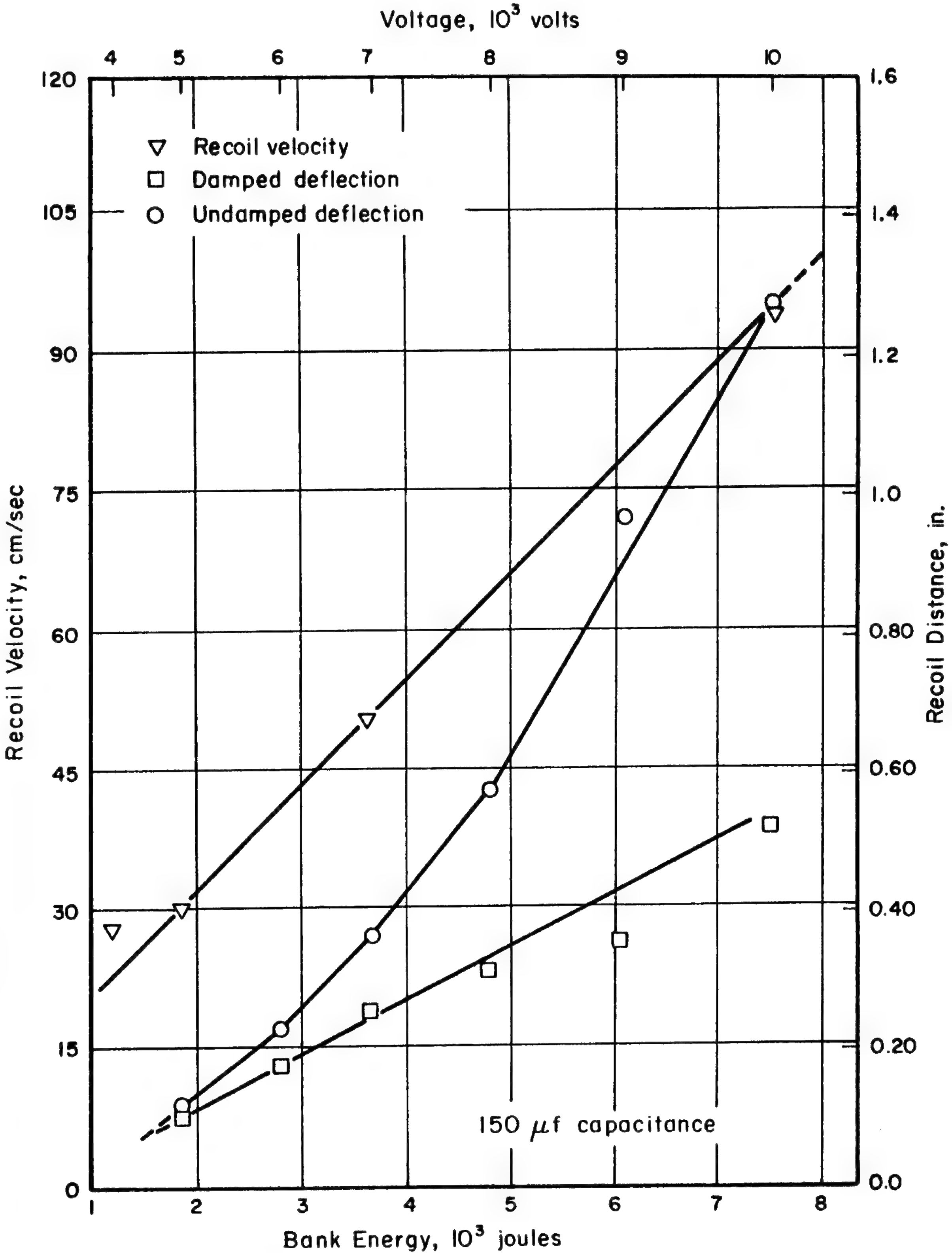


Figure 15.—Recoil data for hammer II described in table II (ref. 5).

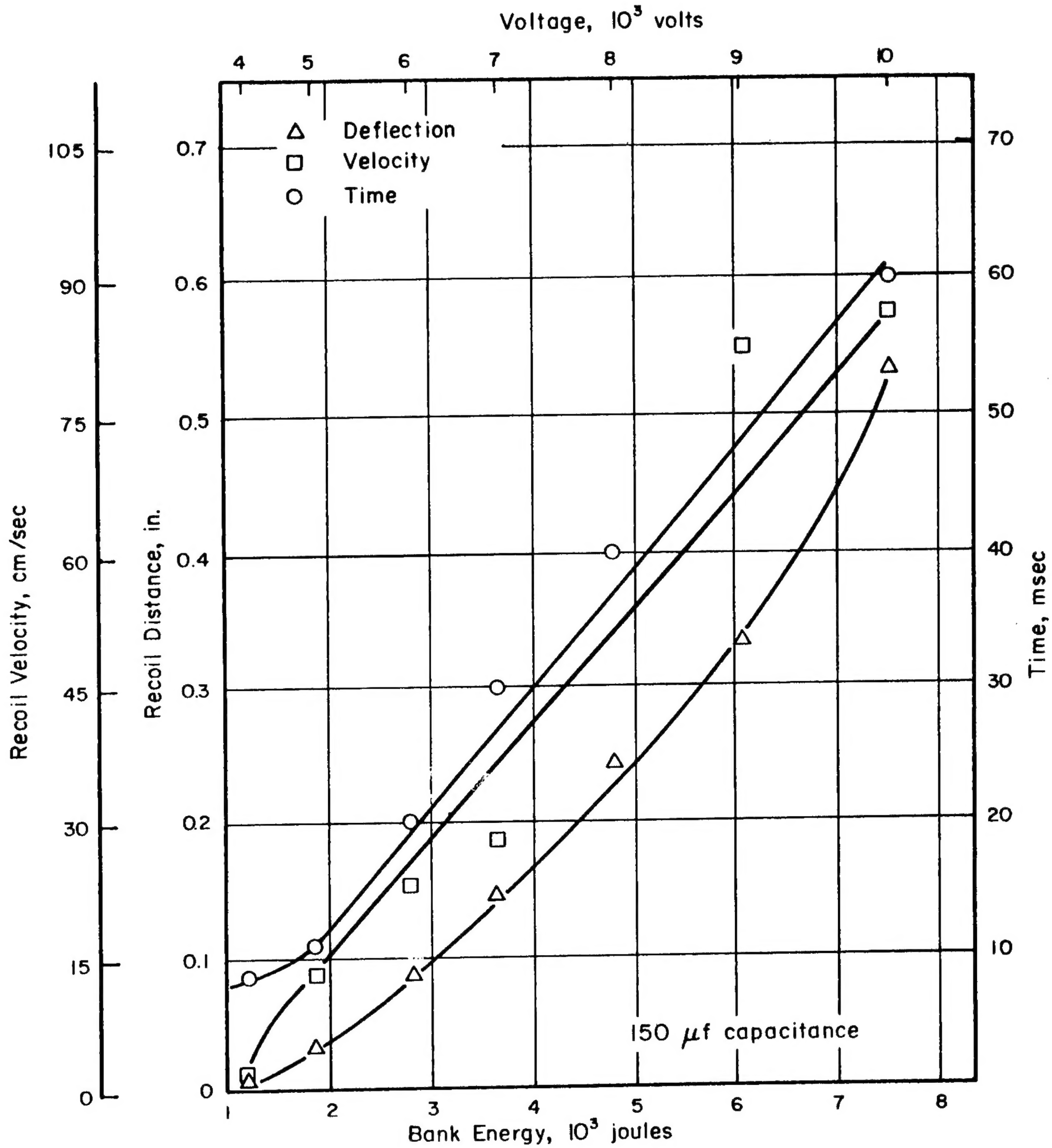


Figure 16.—Recoil data for hammer III described in table II (ref. 5).

was found that the coil starts moving approximately 200 μ sec after the field reaches its maximum energy. This time corresponds to the time required for a sound wave moving at a velocity of 600 m/sec (typical for this plastic) to traverse about 10 cm of reinforced plastic insulation in the coil interior.

The recoil velocity can be calculated from the following equation provided an estimate of the field strength $\overline{B}$ can be made:

$$U = \frac{R_0^2 \overline{B}^2 t_f}{8M}$$

where

U=velocity, cm/sec
R_0=coil radius, cm
$\bar{B}$=field strength, gauss
t_f=time of the pulse, sec
M=coil mass, g
$\bar{B}^2=1/6(B_c)^2$
B_c=the peak field in contact with the work gauss.

Since the calculation and measurements of recoil were obtained from a massive fixed workpiece, the results for a deformable workpiece would be somewhat less. The calculated recoil velocity can, however, be used to design for the maximum recoil conditions which might occur of the coil were to be accidently discharged close to a solid structure.

The effect of the number of coil turns or inductance of the coil on the system was determined by comparing the measured recoil from two coils, 1A and 1B, with the same diameter, 3.937 inches, but different numbers of turns—5, 7, and 10, respectively. The coil with the higher inductance and greater number of turns, 1B, gives the greater recoil velocity for the same amount of field strength. This was attributed to the greater time for discharge. A plot of the recoil velocity at various field strengths is given in figure 17.

In general, it may be said that the lower the coil inductance is, the less the difficulty with recoil for a given energy level. The design of an adequate recoil mechanism should be simpler for a low-inductance coil. It appears that with the presently encountered field strengths, the mounting of the coil to some type of air chamber will be sufficient to overcome the recoil problem at energy levels which may be encountered in the near future.

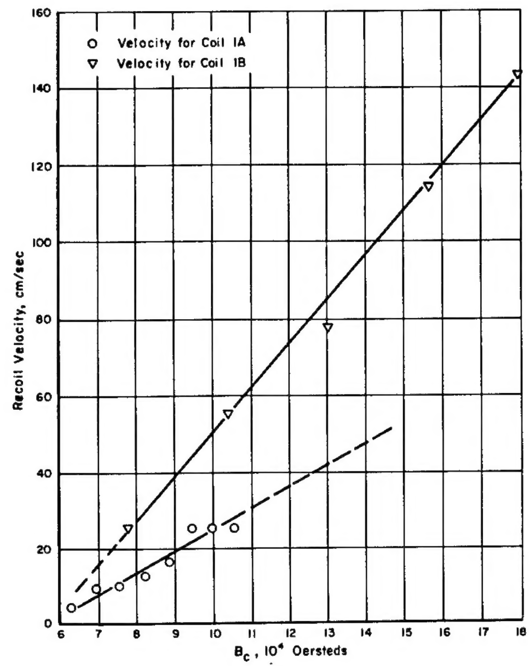


Figure 17.—Graphic comparison of recoil velocities vs. field for coils 1A and 1B described in table II (ref. 5).

Table II.—Magnetic-hammer design and characteristics (ref. 5)

Hammer	1A	1B	1C	II	III
Diameter, inch	3.937	3.937	3.937	7.875	11.811
Turns	5.7	10	10	6.7	6.5
Weight, lb	18.5	18.5	18.5	56.5	85
Coil thickness, in	0.98	0.51	0.98	1.5	1.97
Inductance (L_o), μh	0.37	3.4	2.3	1.1	1.6
Inductance in contact with work (L_c), μh	0.17	1.1	0.77	0.39	0.56
For 150 μf (0.15-μh source):					
¼-cycle τ_r^o, μsec	13	36	30	22	25
¼-cycle in contact with work τ_r^c, μsec	10	22	18	14	16
At 10 kv (7500 joules):					
Peak field (B_o), kilogauss	60	70	70	30	25
Peak field in contact with work (B_c), kilogauss	200	260	200	130	85
Peak current (I_o), ka	170	65	75	105	90
Peak current in contact with work (I_c), ka	220	105	125	160	140
Input energy (E_m^o), kj	5.3	7.3	7.0	6.5	6.7
Input energy in contact with work (E_m^c), kj	4.1	6.5	6.2	5.2	5.7

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